

Ball lightning

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PROPERTIES. Ball lightning is an impressive natural phenomenon for which there is yet no accepted scientific explanation. It consists in flaming balls or fireballs, usually bright white, red, orange or yellow, which appear unexpectedly sometimes near ground following the discharge of a lightning flash, or at midair coming from a cloud.

Most observations of ball lightning are associated with thunderstorms, and they exhibit the following more detailed properties: (i) Their shape is usually spherical or spheroidal with diameters between 10 and 50 cm. (ii) They tend to move horizontally. (iii) The observed distribution of lifetimes has a most probable value between 2 and 5 s and an average value of about 10 s or higher (some cases of more than 1 minute having been reported). (iv) Ball lightning is bright enough to be clearly seen in daylight, the visible output being in the range 10 to 150 W (similar to that of a home electric bulb). (v) Some balls have appeared within aircraft, travelling inside the fuselage along the aisle from front to rear. (vi) There are reports of odours, similar to those of ozone, burning sulfur or nitric oxide, and of sounds, mainly hisses, buzzes or flutters. (vii) Most balls decay silently, but some expire with an explosion. (viii) Ball lightning has killed or injured people and animals and damaged trees, buildings, cars or electric equipment. (ix) Fires having been started showing that there is something hot inside. In such events the released energy has been estimated between 10 kJ and more than 1 MJ. (x) Ball lightning has never been produced in laboratories, in spite of many attempts and some interesting results, including anode spots and luminous objects that decay too quickly. Consequently, the properties of ball lightning are derived from reports by witnesses, who are often excited by the phenomenon and have no scientific training.

A possibly related phenomenon has been observed in submarines, after a short circuit of the batteries. Balls of plasma have appeared at the electrodes that float in air for several seconds. In these occasions, the current was about 150 kA and the energy was estimated between 200 and 400 kJ.

CLASSIFICATION OF THE MODELS. Three main characteristics must be ac-

counted by a successful model but seem very difficult to explain: the tendency to horizontal motion (hot air or plasma in air tends to go upwards), relatively long lifetimes, and contradictions among witnesses. For example, some report that balls are cold since they did not feel any warmth when one passed nearby, while other were burned and needed medical care.

The many different models proposed to explain the phenomenon, can be classified in two groups, according to whether the energy source is internal or external. In the first group, some are based on plasmoids (equilibrium configurations of plasmas), high density plasmas with quantum mechanical properties, closed loops of currents confined by their own magnetic field (in some cases the linking of the currents playing an important role), vortex structures as whirlwinds or rotating spheres, bubbles containing microwave radiation, chemical reactions or combustion, fractal structures, aerosols, filaments of silicon, carbon nanotubes, nuclear processes or new physics, even primordial mini black holes. In the second group, some assume that the balls are powered by electrical discharges or by high-frequency microwave focused from thunderclouds. None of them is generally accepted.

CHEMICAL AND ELECTROMAGNETIC MODELS. The association of ball lightning with electrical discharges suggests strongly that they have an electromagnetic nature. However, Michael Faraday argued that ball lightning can not be an electric phenomenon as it would decay then almost instantaneously, in contrast with its observed lifetime of at least several seconds. In 1964, Finkelstein & Rubinstein used the time independent magnetic virial theorem to put a stringent upper limit to the energy of a fireball. This limit has been viewed as a compelling argument against electromagnetic models, stimulating non-electromagnetic chemical approaches.

Aerosol model have received recently much attention. In one of them (Abrahamson & Dinniss, 2000) a lightning discharge vaporises silicon dioxide in the soil which—after interacting with carbon compounds—is transformed in pure silicon droplets of nanometer scale. These droplets become coated with an insulating coat of oxides and are polarized, after which they become aligned with electric fields and form networks of filaments, in loose structures called “fluff balls”. In another model (Bychkov 2002), the discharges pick up organic material from the soil and transform it in a kind of “spongy ball” that can hold electric charges. Models of this type fail to explain that some balls appear in midair, where there is neither silicon nor organic nor any other similar material.

Electromagnetic models that include chemical effect are promising candidates for an explanation of ball lightning. Indeed, there are now counterarguments to the three main objections that express Faraday’s old opinion in modern language. These are based on: the radiated output, the pinch effect, and magnetic pressure.

The first objection is that the power emitted by a plasma of the size of a ball lightning is too high (one litre of air plasma at 15,000 K emits about 5 MW, several orders of magnitude too much.) This may be however an indication that most of the ball is at ambient temperature, only a small fraction being hot, concentrated in filamentary structures as (hot current streamers). If this fraction is of the order of 1 ppm, the radiated output would be of the order of 10 to 100 W, in agreement with reports.

But the solution to the first problem raises another one. Any plasma current channel inside the ball would be necked and cut in a very short time by the pinch effect (the Lorentz force); thus, a ball structured by such currents could not last long enough. However Chandrasekhar and Woltjer showed in 1958, in an astrophysical context, that plasmas relax to minimum energy states, verifying the condition that the electric current and the magnetic field are parallel so $\nabla \times \mathbf{B} = \lambda \mathbf{B}$, in which there can be no pinch effect since the Lorentz force vanishes. They concluded that such states, known as force-free fields, can confine large amounts of magnetic energy. Although the minimum energy of an uncontained plasma (as in ball lightning) is zero and corresponds to an infinitely expanded magnetic field, an almost force-free condition could be attained first in a very short time at a finite radius, a slow expansion going on afterwards with negligible pinch effect. This could take several seconds.

The third objection is based on the magnetic virial theorem, which states that a system of charges in electromagnetic interactions has no equilibrium state in the absence of external forces, because the large magnetic pressure must produce an explosion with no other force to compensate it. But it is not certain that the fireballs are in equilibrium; they could be just in metastable states with slow evolution, the streamers moreover clearly not being in equilibrium themselves. Still more important, the force-free condition annihilates the magnetic pressure or at least reduces it to a much smaller value if the field is almost force-free. Furthermore, the problem needs a much more complex analysis than what has been done up to now. For instance one must include the thermochemical and quantum effects on the transport processes in the plasma as well as other nonlinear effects. Faddeev and Niemi (2000) have proposed compelling arguments that challenge certain widely held views on plasmas, showing that the virial theorem does allow nontrivial equilibrium states of streamers and electromagnetic fields inside a background of plasma, which are “topologically stable solitons that describe knotted and linked flux tubes of helical magnetic fields”, as was proposed by Rañada *et al* (2000). Therefore it seems that the virial theorem does not support Faraday’s view.

That ball lightning may contain force-free magnetic configurations of plasmas

seems plausible. Because electric conduction in air proceeds through thin channels called streamers—as happens in ordinary lightning—it can be imagined that plasma inside the fireball consists in a self-organised set of metastable highly conductive wire-like or filamentary currents. Furthermore, unusually long-lived filaments (even closed loops) in high density structures have been theoretically predicted and experimentally observed in many plasma systems within a great range of length scales, for instance in in astrophysics, tokamaks and ordinary discharges in air. Thus, filamentary structures are receiving currently much attention.

The strongly nonlinear behaviour of a plasma is enhanced when those filamentary structures appear, leading to a complex non-isotropic system, which should be studied within a more general theory than ideal magneto-hydrodynamics (MHD). Still, the main features of such systems can be described in the frame of resistive MHD. The important dissipative effects depend on the transport coefficients, such as thermal and electrical conductivities, which are highly nonlinear functions of the electromagnetic fields and the temperature, as well as of the chemical and quantum properties.

From the point of view of the MHD approximation, the dimensionless parameters of the plasma inside a ball lightning may be quite similar to those found in other plasma scenarios, implying stable or metastable currents along a set of closed loops in filamentary structures. An interesting and unexplored possibility is the establishment inside the streamers of a quasi-collision-free highly conductive regime in the direction of the magnetic field, which is strong and parallel to the streamers axis. In such a regime, both the electric and the thermal conductivities would become highly anisotropic. The first would be very enhanced along the axis of the streamer. On the other hand, both conductivities would be greatly reduced in the transverse directions, behaving as $1/B^2$ according to classical predictions. In this way, the dissipation and the spreading in the streamers would be much smaller than in ordinary regimes, and should produce a long lived strongly magnetised global plasma structure within an intricate stabilising topology of filamentary currents.

Summarizing, even though the phenomenon of ball lightning has been known for many years, there is still no accepted theory to explain it—the alternatives currently most favoured being the chemical and the electromagnetic models. The latter seem promising now, after recent results show that some classical objections are not always applicable. For instance, a number of filamentary plasma structures have aroused much interest, which are similar to stable plasma scenarios observed in nature, in astrophysics for instance. These kinds of models could possibly embody chemical and electromagnetic elements.

See also Bubbles; Helicity; Magnetohydrodynamics

Further reading

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